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Chamberlain et al.

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(54) **PROGRAMMABLE POWER SUPPLIES FOR CELLULAR BASE STATIONS AND RELATED METHODS OF REDUCING POWER LOSS IN CELLULAR SYSTEMS**

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H04M 19/00 (2006.01)
(Continued)

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CPC ***G05F 1/62*** (2013.01); ***H04M 19/008*** (2013.01); ***H04W 52/00*** (2013.01); ***H04W 52/0206*** (2013.01); *Y02B 60/50* (2013.01)

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CPC .. H04M 1/0262; H04M 19/08; H04M 19/00; Y02E 60/12; H04B 1/3883; H04W 52/02; H04W 52/00; G05F 1/62
USPC 455/571, 572, 561, 13.4, 14.3, 126, 455/127, 461, 462.1; 307/48, 18; 700/297, 700/293
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,659,189 A 4/1972 Kiviranna
6,640,111 B1 * 10/2003 Shapira H01Q 1/246 455/14

(Continued)

FOREIGN PATENT DOCUMENTS

KR 10-2010-0048227 A 5/2010
KR 10-2010-0069332 A 6/2010

OTHER PUBLICATIONS

Jim Williams et al., "2-Wire Virtual Remote Sensing for Voltage Regulators—Clairvoyance Marries Remote Sensing," Linear Technology Brochure, Application Note 126, Oct. 2010, www.linear.com, pp. AN126-1-AN126-22.

(Continued)

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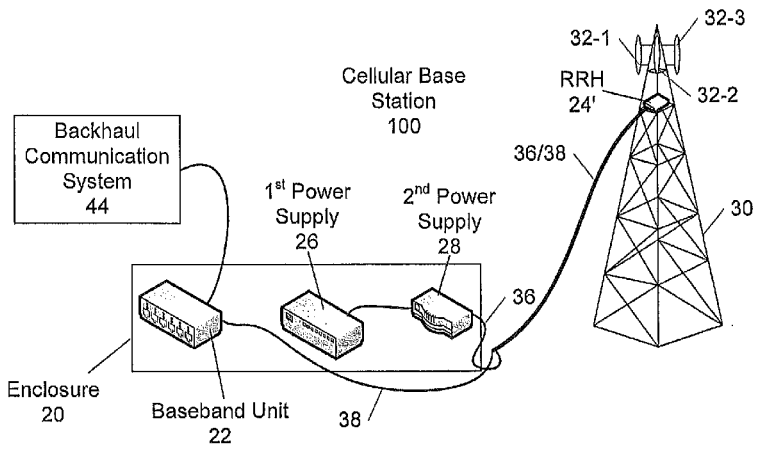
(57) **ABSTRACT**

Methods of powering a radio that is mounted on a tower of a cellular base station are provided in which a direct current ("DC") power signal is provided to the radio over a power cable and a voltage level of the output of the power supply is adjusted so as to provide a substantially constant voltage at a first end of the power cable that is remote from the power supply. Related cellular base stations and programmable power supplies are also provided.

8 Claims, 5 Drawing Sheets



(51) **Int. Cl.**
H04W 52/00 (2009.01)
H04W 52/02 (2009.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,460,381	B2	12/2008	Lanni	
7,508,687	B2	3/2009	Manolescu	
7,739,522	B2	6/2010	Festo et al.	
RE41,655	E *	9/2010	Woodhead	H04W 52/24 455/426.2
7,894,782	B2	2/2011	Rofougaran	
7,949,315	B2	5/2011	Rofougaran	
8,401,497	B2	3/2013	Rofougaran	
8,401,501	B2	3/2013	Rofougaran	
8,412,385	B2	4/2013	Brumett, Jr. et al.	
8,520,549	B2	8/2013	Rofougaran	
8,521,100	B2	8/2013	Rofougaran	
8,526,893	B2	9/2013	Rofougaran	
8,547,164	B2	10/2013	Flores et al.	
8,566,627	B2	10/2013	Halepete et al.	
8,577,359	B2	11/2013	Wesby	
8,600,318	B2	12/2013	Rofougaran	
8,754,622	B2	6/2014	Dobkin et al.	
2003/0085621	A1 *	5/2003	Potega	B60L 11/185 307/18
2007/0024372	A1 *	2/2007	Hagen	H03F 1/0227 330/297
2007/0093204	A1 *	4/2007	Kincard	H01Q 1/246 455/13.3
2008/0272654	A1 *	11/2008	Lontka	G08B 7/06 307/65
2010/0181840	A1 *	7/2010	Coulson	H02J 1/00 307/103
2011/0101937	A1	5/2011	Dobkin et al.	
2012/0069882	A1	3/2012	Nino et al.	
2012/0269509	A1	10/2012	Hultermans	
2012/0317426	A1 *	12/2012	Hunter, Jr.	H04L 12/10 713/300
2013/0051440	A1	2/2013	Rofougaran	
2013/0215804	A1	8/2013	Lu et al.	
2015/0006095	A1	1/2015	Voisine	
2015/0080055	A1	3/2015	Smentek et al.	
2015/0168974	A1 *	6/2015	Mascarenhas	H04L 12/10 700/297

OTHER PUBLICATIONS

International Search Report and Written Opinion Corresponding to International Application No. PCT/US2015/013740; Date of Mailing: Apr. 28, 2015; 17 Pages.

GE Product Data Sheet, CP2000DC54-PE Compact Power Line DC/DC Converter, Aug. 20, 2013, www.ge.com/powerelectronics, 15 pages.

Keithley Product Sheet, Single-Channel Programmable DC Power Supplies, Series 2200, undated, www.keithley.com, 4 pages, Admitted Prior Art.

Invitation to Pay Additional Fees and, Where Applicable, Protest Fee, PCT/US2016/022575, Jun. 23, 2016, 6 pages.

* cited by examiner

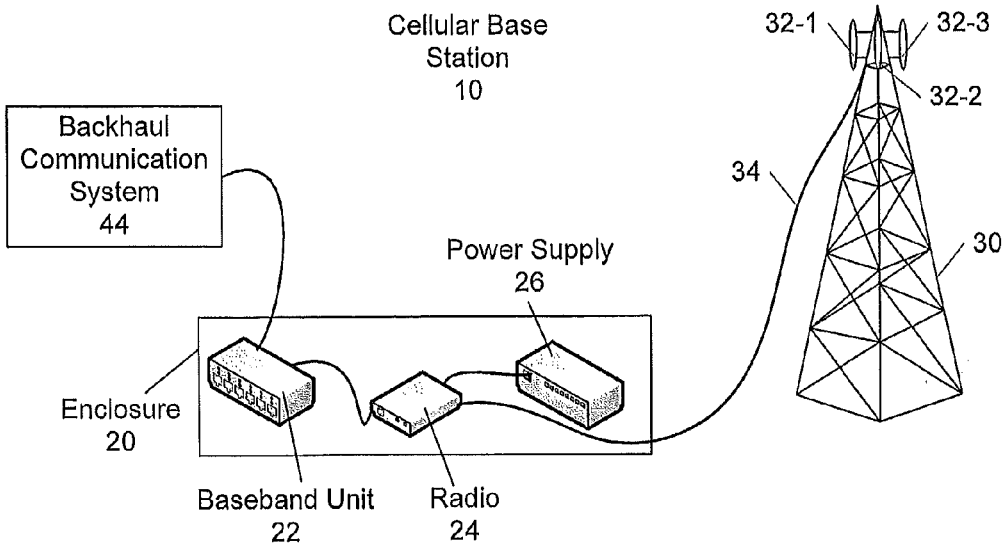


FIG. 1
(Prior Art)

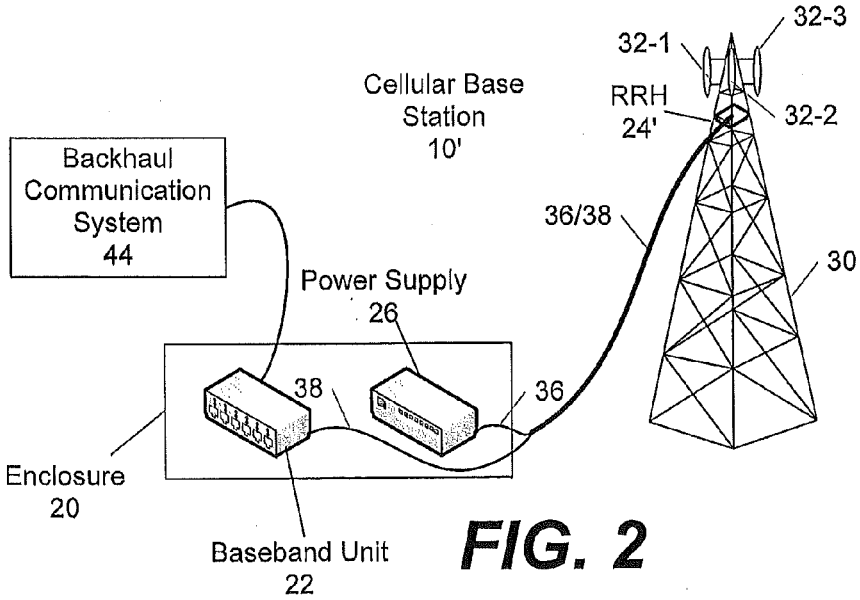


FIG. 2
(Prior Art)

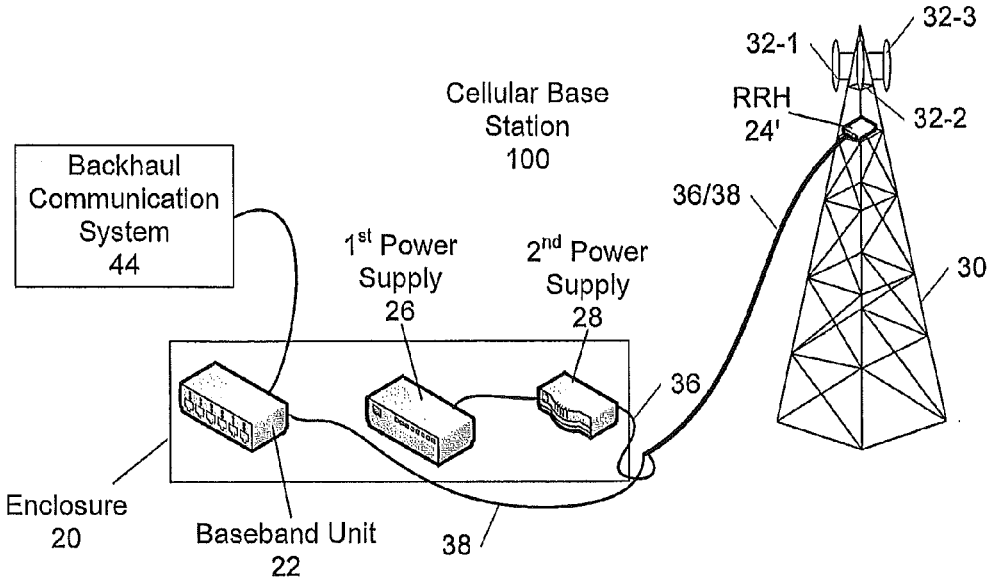

Backhaul Communication System 44
Cellular Base Station 100
1st Power Supply 26
2nd Power Supply 28
RRH 24'
32-1
32-2
32-3
36/38
30
36
Enclosure 20
Baseband Unit 22
38

FIG. 3

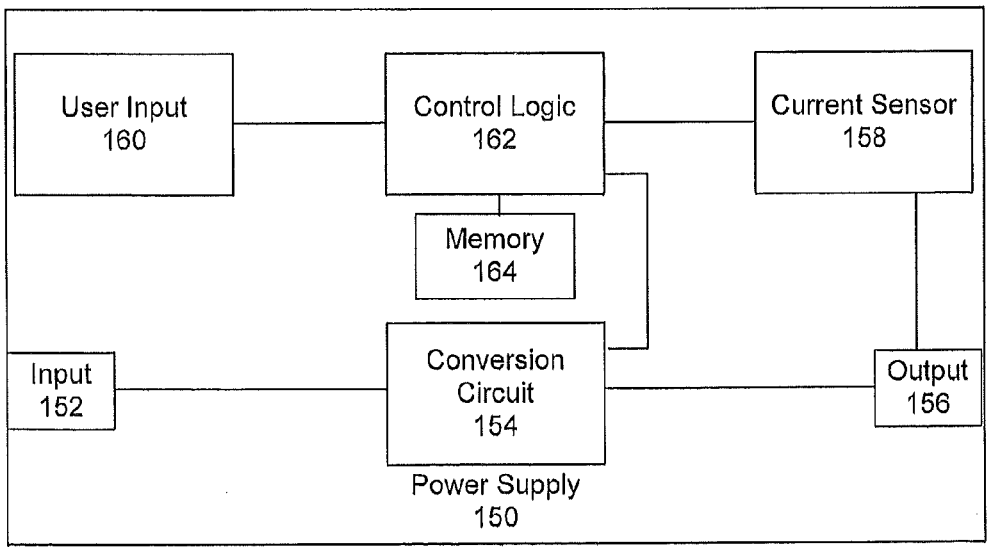

User Input 160
Control Logic 162
Current Sensor 158
Memory 164
Input 152
Conversion Circuit 154
Output 156
Power Supply 150

FIG. 4

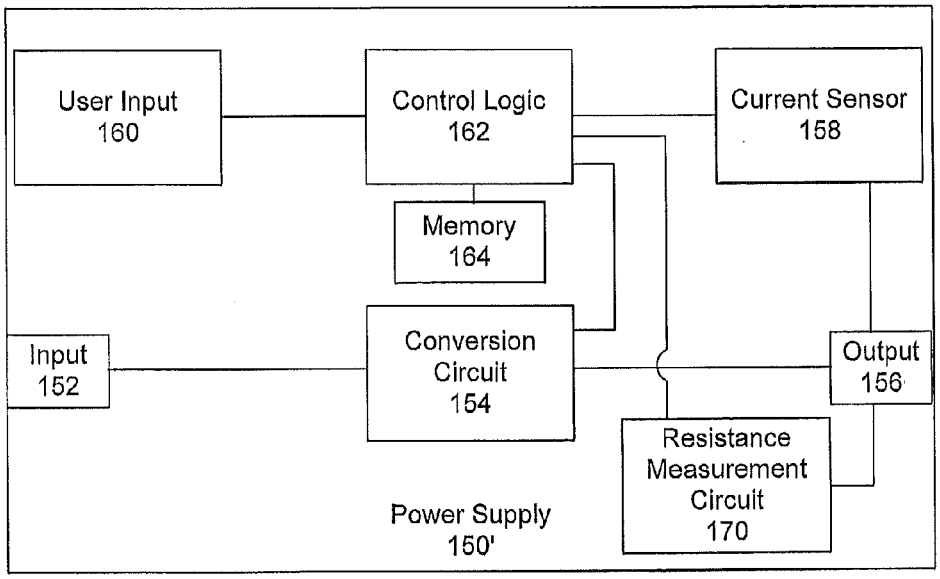

User Input
160
Control Logic
162
Current Sensor
158
Memory
164
Input
152
Conversion
Circuit
154
Output
156
Resistance
Measurement
Circuit
170
Power Supply
150'

FIG. 5

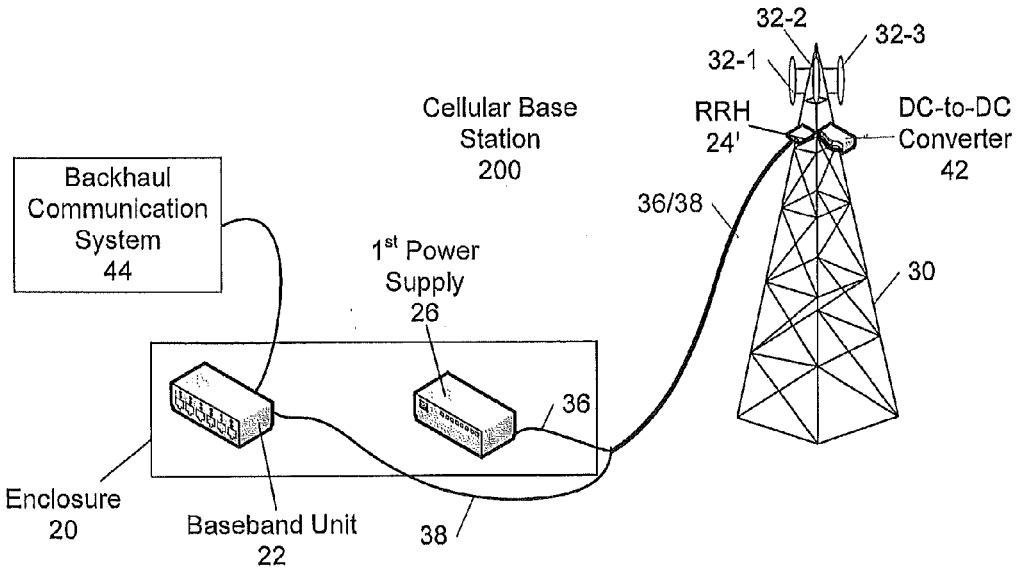

32-2
32-3
32-1
Cellular Base
Station
200
RRH
24'
DC-to-DC
Converter
42
Backhaul
Communication
System
44
36/38
1st Power
Supply
26
30
36
Enclosure
20
Baseband Unit
22
38

FIG. 6

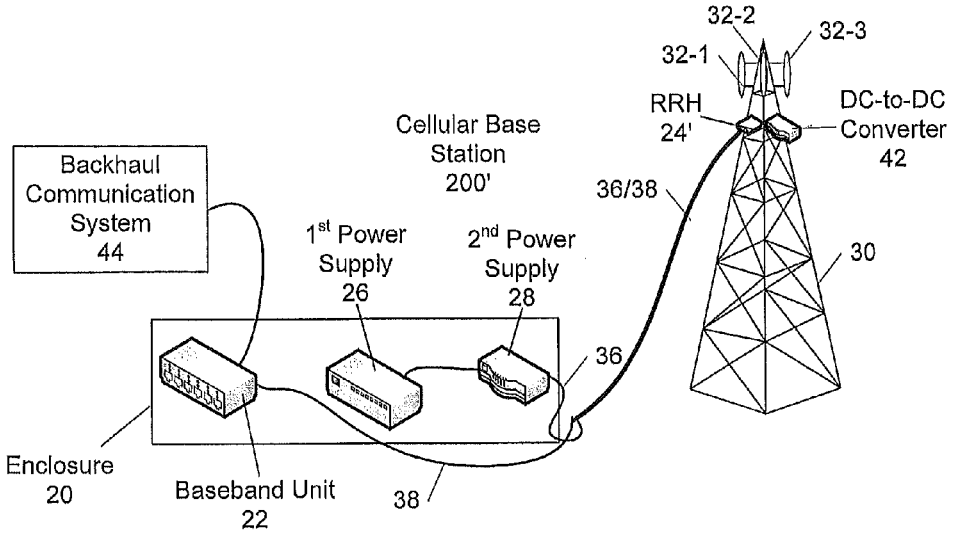

32-2
32-3
32-1
RRH
24'
DC-to-DC
Converter
42
Cellular Base
Station
200'
Backhaul
Communication
System
44
36/38
1st Power
Supply
26
2nd Power
Supply
28
30
36
Enclosure
20
Baseband Unit
22
38

FIG. 7

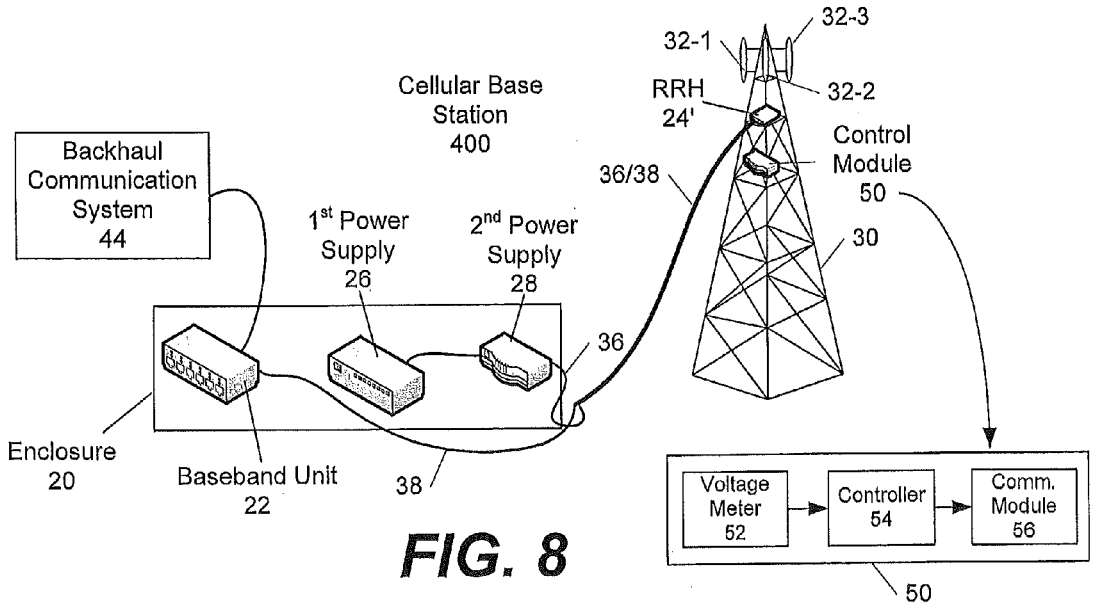

32-3
32-1
32-2
RRH
24'
Cellular Base
Station
400
Control
Module
50
Backhaul
Communication
System
44
36/38
1st Power
Supply
26
2nd Power
Supply
28
30
36
Enclosure
20
Baseband Unit
22
38
Voltage
Meter
52
Controller
54
Comm.
Module
56
50

FIG. 8

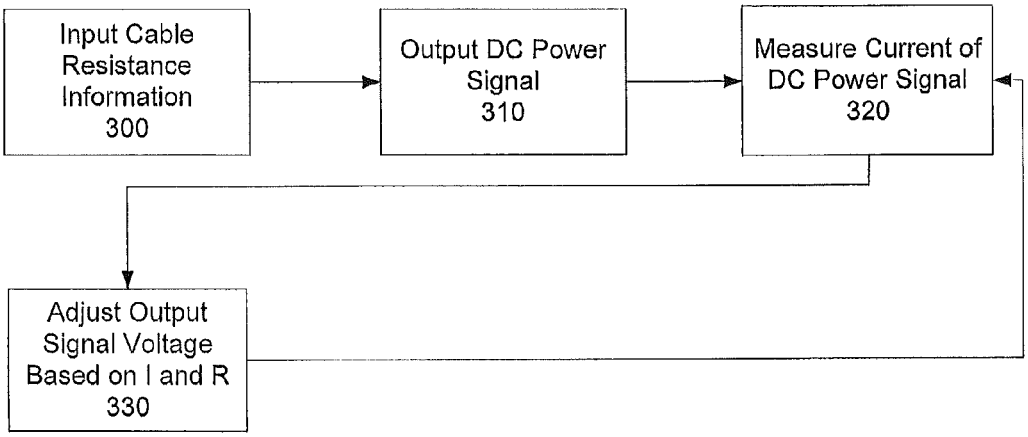

Input Cable Resistance Information 300
Output DC Power Signal 310
Measure Current of DC Power Signal 320
Adjust Output Signal Voltage Based on I and R 330

FIG. 9

PROGRAMMABLE POWER SUPPLIES FOR CELLULAR BASE STATIONS AND RELATED METHODS OF REDUCING POWER LOSS IN CELLULAR SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims priority under 35 U.S.C. §119 to U.S. Provisional Patent Application Ser. No. 61/940,631, filed Feb. 17, 2014, the entire contents of which is incorporated herein by reference as if set forth in its entirety.

FIELD OF THE INVENTION

The present invention relates generally to cellular communications systems and, more particularly, to power supplies for cellular base stations that may exhibit reduced power loss.

BACKGROUND

Cellular base stations typically include, among other things, a radio, a baseband unit, and one or more antennas. The radio receives digital information and control signals from the baseband unit and modulates this information into a radio frequency ("RF") signal that is then transmitted through the antennas. The radio also receives RF signals from the antenna and demodulates these signals and supplies them to the baseband unit. The baseband unit processes demodulated signals received from the radio into a format suitable for transmission over a backhaul communications system. The baseband unit also processes signals received from the backhaul communications system and supplies the processed signals to the radio. A power supply may also be provided that generates suitable direct current ("DC") power signals for powering the baseband unit and the radio. For example, the radio is often powered by a (nominal) 48 Volt DC power supply in cellular systems that are currently in use today. A battery backup is also typically provided to maintain service for some period of time during power outages.

In order to increase coverage and signal quality, the antennas in many cellular base stations are located at the top of a tower, which may be, for example, about fifty to two hundred feet tall. Until fairly recently, the power supply, baseband unit and radio were all located in an equipment enclosure at the bottom of the tower to provide easy access for maintenance, repair and/or later upgrades to the equipment. Coaxial cable(s) were routed from the equipment enclosure to the top of the tower that carried signal transmissions between the radio and the antennas.

FIG. **1** schematically illustrates a conventional cellular base station **10**. As shown in FIG. **1**, the cellular base station **10** includes an equipment enclosure **20** and a tower **30**. The equipment enclosure **20** is typically located at the base of the tower **30**, as shown in FIG. **1**. A baseband unit **22**, a radio **24** and a power supply **26** are located within the equipment enclosure **20**. The baseband unit **22** may be in communication with a backhaul communications system **44**. A plurality of antennas **32** (e.g., three sectorized antennas **32-1**, **32-2**, **32-3**) are located at the top of the tower **30**. Three coaxial cables **34** (which are bundled together in FIG. **1** to appear as a single cable) connect the radio **24** to the antennas **32**. The antennas **32** are passive (unpowered) devices and hence none of the equipment at the top of the tower **30** require electrical power. Note that herein when multiple units of an element are provided, each individual unit may be referred to individually by the reference numeral for the element followed by a dash and the number for the individual unit (e.g., antenna **32-2**), while multiple units of the element may be referred to collectively by their base reference numeral (e.g., the antennas **32**).

In recent years, a shift has occurred and the radio **24** is now more typically located at the top of the tower **30** in new or upgraded cellular installations. Radios that are located at the top of the tower **30** are typically referred to as remote radio heads ("RRH") **24'**. Using RRHs **24'** may significantly improve the quality of the cellular data signals that are transmitted and received by the cellular base station as the use of RRHs **24'** may reduce signal transmission losses and noise. In particular, as the coaxial cable runs up the tower may be 100-200 feet or more, the signal loss that occurs in transmitting signals at cellular frequencies (e.g., 1.8 GHz, 3.0 GHz, etc.) over the coaxial cable may be significant. Because of this loss in signal power, the signal-to-noise ratio of the RF signals may be degraded in systems that locate the radio **24** at the bottom of the tower **30** as compared to cellular base stations where RRHs **24'** are located at the top of the tower **30** next to the antennas **32** (note that signal losses in the cabling connection between the baseband unit **22** at the bottom of the tower **30** and the RRH **24'** at the top of the tower **30** may be much smaller, as these signals are transmitted at baseband frequencies as opposed to RF frequencies).

FIG. **2** is a schematic diagram that illustrates a cellular base station **10'** according to this newer architecture. As shown in FIG. **2**, the baseband unit **22** and the power supply **26** may still be located at the bottom of the tower **30** in the equipment enclosure **20**. The radio **24** in the form of an RRH **24'** is located at the top of the tower **30** immediately adjacent to the antennas **32**. While the use of tower-mounted RRHs **24'** may improve signal quality, it also, unfortunately, requires that DC power be delivered to the top of the tower **30** to power the RRH **24'**. In some cases, the DC power may be delivered over a coaxial cable (not shown) that also carries communications between the baseband unit **22** and the RRH **24'**. As shown in FIG. **2**, more typically a fiber optic cable **38** connects the baseband unit **22** to the RRH **24'** (as fiber optic links may provide greater bandwidth and lower loss transmissions), and a separate power cable **36** is provided for delivering the DC power signal to the RRH **24'**. The separate power cable **36** is typically bundled with the fiber optic cable **38** so that they may be routed up the tower **30** together.

SUMMARY

Pursuant to embodiments of the present invention, methods of powering a radio that is mounted on a tower of a cellular base station (or other location remote from an associated baseband unit) are provided in which a DC power signal is output from a power supply and the DC power signal that is output from the power supply is supplied to the radio over a power cable. A voltage level of the DC power signal that is output from the power supply is adjusted so that the DC power signal at a radio end of the power cable that is remote from the power supply has a substantially constant voltage notwithstanding variation in a current level of the DC power signal.

In some embodiments, the power supply may be a programmable power supply, and the method may further include inputting information to the power supply from which the voltage level of the DC power signal that is output from the power supply can be computed that will provide the

DC power signal at the radio end of the power cable that has the substantially constant voltage. In such embodiments, the information that is input to the power supply may be a resistance of the power cable, or may be a length of the power cable and a diameter of the conductive core of the power cable.

In some embodiments, a current level of the DC power signal that is output from the power supply may be measured, and the voltage level of the DC power signal that is output by the power supply may be automatically adjusted in response to changes in the measured output current of the DC power signal that is output from the power supply to provide the DC power signal at the radio end of the power cable that has the substantially constant voltage.

In some embodiments, the programmable power supply may be a DC-to-DC converter that receives a DC power signal that is output from a second power supply and adjusts a voltage level of the DC power signal that is output from the second power supply to provide the DC power signal at the radio end of the power cable that has the substantially constant voltage. The substantially constant voltage may be a voltage that exceeds a nominal power signal voltage of the radio and which is less than a maximum power signal voltage of the radio.

In some embodiments, a signal may be transmitted over the power cable that is used to determine an electrical resistance of the power cable. In some embodiments, the substantially constant voltage may be significantly higher than a maximum power signal voltage of the radio, and a tower-mounted DC-to-DC converter may be used to reduce a voltage of the power signal at the radio end of the power cable to a voltage that is less than the maximum power supply voltage of the radio.

Pursuant to further embodiments of the present invention, cellular base station systems are provided that include a tower with at least one antenna mounted thereon, an RRH mounted on the tower, a baseband unit that is in communication with the RRH, a programmable power supply located remotely from the RRH; and a power cable having a first end that receives a DC power signal from the programmable power supply and a second end that provides the DC power signal to the RRH. The programmable power supply is configured to provide a substantially constant voltage at the second end of the power cable by adjusting a voltage level of the DC power signal output by the programmable power supply based on the current level output by the programmable power supply and a resistance of the power cable.

In some embodiments, the programmable power supply may include a user interface that is configured to receive a resistance of the power cable and/or information regarding characteristics of the power cable from which the resistance of the power cable may be calculated. The programmable power supply may further include a current measurement module that measures a current output by the power supply. The programmable power supply may also include a feedback loop that adjusts the voltage level of the DC power signal output of the power supply based on the measured current output by the power supply.

Pursuant to still further embodiments of the present invention, programmable power supplies are provided that include an input; a conversion circuit that is configured to convert an input signal into a DC output signal that is output through an output port; a current sensor that senses an amount of current output through the output port; a user input that is configured to receive information relating to the resistance of a cabling connection between the programmable power supply output port and a radio; and a control module that is configured to control the conversion circuit in response to information relating to the resistance of the cabling connection and the sensed amount of current to adjust the voltage of the output signal that is output through the output port so that the voltage at the far end of the cabling connection may remain substantially constant despite changes in the current drawn by the radio.

In some embodiments, the information relating to the resistance of the cabling connection may comprise a length of the cabling connection and a size of the conductor of the cabling connection.

Pursuant to additional embodiments of the present invention, methods of powering a cellular radio that is located remotely from a power supply and an associated baseband unit and that is connected to the power supply by a cabling connection are provided in which a DC power signal is output from the power supply and the DC power signal that is output from the power supply is supplied to the radio over the cabling connection. A voltage level of the DC power signal that is output from the power supply is adjusted in response to a current level of the DC power signal that is output from the power supply so that the voltage of the DC power signal at a radio end of the cabling connection is maintained at a pre-selected level, range or pattern.

In some embodiments, the voltage level of the DC power signal that is output from the power supply is adjusted in response to a feedback signal that is transmitted to the power supply from a remote location. The feedback signal may include information regarding the measured voltage of the DC power signal at the radio end of the power cable.

Pursuant to yet additional embodiments of the present invention, methods of powering a radio that is mounted on a tower of a cellular base station (or other location remote from an associated baseband unit) are provided in which a DC power signal is output from a power supply and the DC power signal that is output from the power supply is supplied to the radio over a power cable. A voltage of the DC power signal is measured at a radio end of the power cable that is remote from the power supply. Information regarding the measured voltage of the DC power signal at the radio end of the power cable is communicated to the power supply. A voltage level of the DC power signal that is output from the power supply is adjusted in response to the received information regarding the measured voltage of the DC power signal at the radio end of the power cable.

In some embodiments, the voltage level of the DC power signal that is output from the power supply may be adjusted in response to the received information to maintain the DC power signal at the radio end of the power cable at a substantially constant voltage notwithstanding variation in a current level of the DC power signal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a simplified, schematic view of a traditional cellular base station architecture.

FIG. **2** is a simplified, schematic view of a conventional cellular base station in which a remote radio head is located at the top of the antenna tower.

FIG. **3** is a simplified, schematic view of a cellular base station according to embodiments of the present invention.

FIG. **4** is a schematic block diagram of a programmable power supply according to embodiments of the present invention.

FIG. **5** is a schematic block diagram of a programmable power supply according to further embodiments of the present invention.

FIG. **6** is a simplified, schematic view of a cellular base station according to still further embodiments of the present invention.

FIG. **7** is a simplified, schematic view of a cellular base station according to yet additional embodiments of the present invention.

FIG. **8** is a simplified, schematic view of a cellular base station according to yet further embodiments of the present invention.

FIG. **9** is a flow chart illustrating operations of methods according to embodiments of the present invention.

DETAILED DESCRIPTION

Pursuant to embodiments of the present invention, methods for delivering DC power to a remote radio head ("RRH") of a cellular base station are provided, along with related cellular base stations and programmable power supplies. These methods, systems and power supplies may allow for lower power supply currents, which may reduce the power loss associated with delivering the DC power signal from the power supply at the base of a tower of the cellular base station to the RRH at the top of the tower. Since cellular towers may be hundreds of feet tall and the voltage and currents required to power the RRH may be quite high (e.g., about 50 Volts at about 20 Amperes of current), the power loss that may occur along the hundreds of feet of cabling may be significant. Thus, the methods according to embodiments of the present invention may provide significant power savings which may reduce the costs of operating a cellular base station.

The DC voltage of a power signal that is supplied to an RRH from a power supply over a power cable may be determined as follows:

$$V_{RRH}=V_{PS}-V_{Drop} \quad (1)$$

where V_{RRH} is the DC voltage of the power signal delivered to the RRH, V_{PS} is the DC voltage of the power signal that is output by the power supply, and V_{Drop} is the decrease in the DC voltage that occurs as the DC power signal traverses the power cable connecting the power supply to the RRH. V_{Drop} may be determined according to Ohm's Law as follows:

$$V_{Drop}=I_{RRH}*R_{Cable} \quad (2)$$

where R_{Cable} is the cumulative electrical resistance (in Ohms) of the power cable connecting the power supply to the RRH and I_{RRH} is the average current (in Amperes) flowing through the power cable to the RRH.

The electrical resistance R_{Cable} of the power cable is inversely proportional to the diameter of the conductor of the power cable (assuming a conductor having a circular cross-section). Thus, the larger the diameter of the conductor (i.e., the lower the gauge of the conductor), the lower the resistance of the power cable. Typically, power cables utilize copper conductors due to the low resistance of copper. Copper resistance is specified in terms of unit length, typically milliohms (mΩ)/ft; as such, the cumulative electrical resistance of the power cable increases with the length of the cable. Thus, the longer the power cable, the higher the voltage drop V_{Drop}.

Typically, a minimum required voltage for the power signal, a nominal or recommended voltage for the power signal and a maximum voltage for the power signal will be specified for the RRH. Thus, the power supply at the base of the tower must output a voltage V_{PS} such that V_{RRH} will be between the minimum and maximum specified voltages for the power signal of the RRH. As V_{Drop} is a function of the current I_{RRH} that is supplied to the RRH (see Equation 2 above), if V_{PS} (the voltage output by the power supply) is constant, then the voltage V_{RRH} of the power signal that is delivered to the RRH will change with the variation in current drawn by the RRH. Conventionally, the voltage output by the power supply (V_{PS}) is set to ensure that a power signal having the nominal voltage is supplied to the RRH (or at least a value above the minimum required voltage for the power signal) when the RRH draws the maximum anticipated amount of current.

The power that is lost (P_{Loss}) in delivering the power signal to the RRH over a power cable may be calculated as follows:

$$P_{Loss}=V_{Cable}*I_{RRH}=(I_{RRH}*R_{Cable})*I_{RRH}=I_{RRH}^{2}*R_{Cable} \quad (3)$$

where V_{Cable}=the average voltage drop in Volts along the power cable. In order to reduce or minimize P_{Loss}, the power supply may be set to output a DC power signal that, when it arrives at the RRH, will have the maximum voltage specified for the RRH, as the higher the voltage of the power signal that is delivered to the RRH the lower the current I_{RRH} of the power signal on the power cable. As is apparent from Equation 3 above, the lower the current I_{RRH} of the power signal on the power cable, the lower the power loss P_{Loss}.

Pursuant to embodiments of the present invention, the power supply may comprise a programmable power supply which may (1) sense the current being drawn by the RRH (or another equivalent parameter) and (2) adjust the voltage of the power signal that is output by the power supply to substantially maintain the voltage of the power signal that is supplied to the RRH at or near a desired value, which may be, for example, the maximum voltage for the power signal that may be input to the RRH. In order to accomplish this, the resistance of the power cable may be input to the programmable power supply or, alternatively, other information such as, for example, the length and size of the power cable, or the impedance of the power cable, may be input to the programmable power supply and the programmable power supply may determine the resistance of the power cable from this information. As the current drawn by the RRH varies, the programmable power supply may adjust the voltage of its output power signal to a voltage level that will deliver a power signal having a preselected voltage (e.g., the maximum supply voltage of the RRH minus a buffer) to the RRH. As shown by Equation 3 above, this will reduce or minimize the power loss along the power cable, and hence may reduce the cost of powering the RRH. As a typical RRH may require about a kilowatt of power and may run 24 hours a day, seven days a week, and as a large number of RRHs may be provided at each cellular base station (e.g., three to twelve), the power savings may be significant.

Embodiments of the present invention will now be discussed in more detail with reference to FIGS. **3-7**, in which example embodiments of the present invention are shown.

FIG. **3** is a schematic block diagram of a cellular base station **100** according to embodiments of the present invention. As shown in FIG. **3**, the cellular base station **100** includes an equipment enclosure **20** and a tower **30**. The tower **30** may be a conventional antenna or cellular tower or may be another structure such as a utility pole or the like. A baseband unit **22**, a first power supply **26** and a second power supply **28** are located within the equipment enclosure **20**. An RRH **24'** and plurality of antennas **32** (e.g., three sectorized antennas **32-1**, **32-2**, **32-3**) are mounted on the tower **30**, typically near the top thereof.

The RRH **24'** receives digital information and control signals from the baseband unit **22** over a fiber optic cable **38** that is routed from the enclosure **20** to the top of the tower **30**. The RRH **24'** modulates this information into a radio frequency ("RF") signal at the appropriate cellular frequency that is then transmitted through one or more of the antennas **32**. The RRH **24'** also receives RF signals from one or more of the antennas **32**, demodulates these signals, and supplies the demodulated signals to the baseband unit **22** over the fiber optic cable **38**. The baseband unit **22** processes the demodulated signals received from the RRH **24'** and forwards the processed signals to the backhaul communications system **44**. The baseband unit **22** also processes signals received from the backhaul communications system **44** and supplies them to the RRH **24'**. Typically, the baseband unit **22** and the RRHs **24** each include optical-to-electrical and electrical-to-optical converters that couple the digital information and control signals to and from the fiber optic cable **38**.

The first power supply **26** generates one or more direct current ("DC") power signals. The second power supply **28** in the embodiment of FIG. **3** comprises a DC-to-DC converter that accepts the DC power signal output by the first power supply **26** as an input and outputs a DC power signal having a different voltage. A power cable **36** is connected to the output of the second power supply **28** and is bundled together with the fiber optic cable **38** so that the two cables **36**, **38** may be routed up the tower **30** as an integral unit. While the first power supply **26** and the second power supply **28** are illustrated as separate power supply units in the embodiment of FIG. **3**, it will be appreciated that the two power supplies **26**, **28** may be combined into a single power supply unit in other embodiments.

As noted above, pursuant to embodiments of the present invention, DC power supplies are provided that may deliver a power signal to a remote RRH with reduced power loss. In the embodiment of FIG. **3**, the power supply **28** comprises a programmable power supply that receives an input DC power signal from power supply **26** and outputs a DC power signal to the power cable **36**. The voltage of the DC power signal output by the power supply **28** may vary in response to variations in the current of the DC power signal drawn from the power supply **28** by the RRH **24'**. In particular, the voltage of the DC power signal output by the power supply **28** may be set so that the voltage of the DC power signal at the far end of the power cable **36** (i.e., the end adjacent the RRH **24'**) is relatively constant. If the voltage of the DC power signal at the far end of power cable **36** is set to be approximately the maximum specified voltage for the power signal of the RRH **24'**, then the power loss associated with supplying the DC power signal to the RRH **24'** over the power cable **36** may be reduced, since the higher DC power signal voltage will correspondingly reduce the current of the DC power signal that is supplied over the power cable **36**.

State-of-the-art RRHs are most typically designed to be powered by a 48 Volt (nominal) DC power signal. While the minimum DC power signal voltage at which the RRH **24'** will operate and the maximum DC power signal voltage that may be provided safely to the RRH **24'** without the threat of damage to the RRH **24'** vary, typical values are a 38 Volt minimum DC power signal voltage and a 56 Volt maximum DC power signal voltage. Thus, according to embodiments of the present invention, the programmable power supply **28** may be designed to deliver a DC power signal having a relatively constant voltage of, for example, about 54 or 52 Volts at the far end of the power cable **36** (i.e., about, 2-4 Volts less than the maximum DC power signal voltage for the RRH **24'**) in order to reduce the power loss associated with the voltage drop that the DC power signal experiences traversing the power cable **36**.

In order to maintain the voltage of the DC power signal at the far end of the power cable **36** at or near a predetermined value it may be necessary to know two things. First, the current of the DC power signal drawn from the power supply must be known, as Equations 1 and 2 show that V_{RRH} is a function of I_{RRH}. Second, the resistance R_{Cable} of the power cable **36** must also be known, as it too affects the voltage drop. The programmable power supplies according to embodiments of the present invention may be configured to measure, estimate, calculate or receive both values.

For example, FIG. **4** is a block diagram of a programmable power supply **150** in the form of a DC-to-DC converter according to certain embodiments of the present invention that may be used as the power supply **28** of FIG. **3**. As shown in FIG. **4**, the programmable power supply **150** includes an input **152**, a conversion circuit **154** and an output **156**. The power supply **150** further includes a current sensor **158**, a user input **160**, control logic **162** and a memory **164**.

The input **152** may receive a DC power signal such as the DC power signal output by power supply **26** of FIG. **3**. The DC power signal that is received at input **152** may be a DC power signal having a relatively constant voltage in some embodiments. The conversion circuit **154** may be a circuit that is configured to convert the voltage of the signal received at input **152** to a different DC voltage. A wide variety of DC conversion circuits are known in the art, including, for example, electronic, electrochemical and electromechanical conversion circuits. Most typically electronic circuits using inductors or transformers are used to provide high efficiency voltage conversion. The output **156** may output the DC power signal having the converted voltage.

The current sensor **158** may be any appropriate circuit that senses the current level of the DC power signal output through the output **156**. The current drawn by the RRH **24'** may vary over time depending upon, for example, the number of carriers that are transmitting at any given time and whether the RRH is in a steady-state mode, powering up or rebooting. The current sensor **158** may sense the current level of the DC power signal at output **156** and provide the sensed current level to the control logic **162**. The control logic **162** may then adjust parameters of the conversion circuit **154** so as to adjust the voltage of the DC power signal output through output **156** so that the voltage at the far end of the power cable **36** that is attached to output **156** may remain substantially constant despite changes in the current drawn by the RRH **24'** and corresponding changes in the voltage drop that occurs over the power cable **36**.

While FIG. **4** illustrates a power supply **150** that comprises a DC-to-DC converter, it will be appreciated that in other embodiments an AC-to-DC converter may be used instead. In such embodiments, the input **152** receives an alternating current ("AC") power signal and the conversion circuit **154** converts the AC power signal to a DC power signal and also adjusts the voltage level of the DC power signal that is output through output **156** to an appropriate level in the manner discussed above.

As noted above, in some embodiments, the voltage of the power signal that is output by the power supply **150** may be set so that the voltage at the far end of the power cable **36** remains at or near a predetermined voltage level that is just under a maximum power signal voltage level that the RRH **24'** may handle. In order to achieve this, it is necessary to know the voltage drop that the DC power signal will experience traversing the power cable **36**, as this voltage

drop affects the voltage of the DC power signal at the far end of the power cable **36**. In some embodiments, the user input **160** to the power supply **150** allows a user to input a cumulative resistance value for the power cable **36** which the user may obtain by, for example, calculation (based on the length, size and material of the conductor of the power cable **36**), measurement (done, for example, by transmitting a signal over the power cable **36** and measuring the voltage of the signal output at the far end of the power cable **36**) or a combination thereof (e.g., measuring or estimating a cumulative impedance value for the power cable **36** and converting this cumulative impedance value into a cumulative resistance value). In other embodiments, the user may input physical characteristics of the power cable **36** such as size, length, conductor material, model number, etc.) and algorithms, equations, look-up tables and the like that are stored in the memory **164** of the power supply **150** may be used to calculate or estimate the resistance of the power cable **36**.

In some embodiments, the second power supply **28** of FIG. **3** may further be configured to measure a resistance of the power cable **36**. For example, FIG. **5** is a block diagram of a programmable power supply **150'** according to further embodiments of the present invention that may be used to implement the power supply **28** of FIG. **3**. The power supply **150'** is very similar to the power supply **150** of FIG. **4**, except that it further includes a cable resistance measurement circuit **170** that may be used to measure a resistance of the power supply cable. The cable resistance measurement circuit **170** may be implemented in a variety of ways. For example, in some embodiments, the cable resistance measurement circuit **170** may transmit a voltage pulse onto the power cable and measure the reflected return pulse (the far end of the power cable may be terminated with a termination having known characteristics). The current of the voltage pulse may be measured, as well as the voltage level of the reflected return pulse. The control logic **162** may then apply Ohm's law to calculate the resistance of the power cable. In other embodiments, at the far end of the power cable the two conductors thereof may be shorted and a voltage pulse may again be transmitted through the power cable. The current level of the pulse and the voltage level of the return pulse may be measured and the control logic **162** may again use these measured values to calculate the resistance of the power cable. In other embodiments, the DC resistance can be measured by transmitting alternating current signals at different frequencies over the power cable and measuring the amplitude and phase shift of these signals at the far end of the cable. The DC resistance may then be calculated using the measured results. Other ways of measuring the resistance of a wire segment are known to those of skill in the art and may be used instead of the example methods listed above.

It will also be appreciated that in other embodiments the resistance measurement circuit **170** may measure an impedance of the power cable and use this measured impedance value to determine the resistance of the power cable. It will also be appreciated that the power supply **150'** may alternatively comprise an AC-to-DC converter, similar to power supply **150** discussed above.

Another technique for reducing the power loss associated with supplying power to a tower-mounted RRH of a cellular base station is to dramatically increase the voltage of the DC power signal fed to the power cable that supplies the DC power signal to the RRH (i.e., well beyond the maximum voltage for the DC power signal that can be handled by the RRH), and then using a tower-mounted DC-to-DC converter power supply to step-down the voltage of the DC power signal to a voltage level that is appropriate for the RRH. As the increased voltage reduces the current necessary to supply the wattage required by the RRH, the power loss along the power cable may be reduced (see Equation 2 above). This is referred to as a "Buck-Boost" scheme where the first DC-to-DC converter at the bottom of the tower is a "Boost" converter that increases the voltage of the DC power signal above the necessary level to operate the RRH and the second DC-to-DC converter at the top of the tower is a "Buck" converter that reduces the voltage of the DC power signal to a desired level. FIG. **6** is a simplified, schematic view of a cellular base station **200** that implements such a technique.

As shown in FIG. **6**, the cellular base station **200** is similar to the cellular base station **100** described above with reference to FIG. **3**, except that the cellular base station **200** further includes a third power supply **42** in the form of a tower-mounted DC-to-DC converter. In the depicted embodiment, the second power supply **28** of FIG. **3** is omitted, and the first power supply **26** is configured to supply a DC power signal having a voltage that is significantly higher than the maximum voltage for the DC power signal that may be supplied to the RRH **24'** (e.g., a 150 volt DC power signal). This high voltage DC power signal may experience significantly less power loss when traversing the power cable **36**. The DC-to-DC converter **42** is mounted at the top of the tower **30** between the far end of cable **36** and the RRH **24'**. The DC-to-DC converter **42** may be a Buck converter that decreases the voltage of the DC power signal received over the power cable **36** to a voltage level appropriate for supply to the RRH **24'**.

As is shown in FIG. **7**, in other embodiments, the second power supply **28** may be included in the form of, for example, a DC-to-DC Boost power converter **28** that supplies a high voltage DC power signal (e.g., 150 volts) to the power cable **36**. In this embodiment, a DC-to-DC converter is provided at both ends of the power cable **36** so that both of the above-described techniques for reducing power losses in the power cable **36** may be implemented. In particular, the second power supply **28** may output a DC power signal having high voltage (e.g., on the order of 150 volts) that fluctuates with power requirements of the load so that the DC power signal that is supplied at the far end of power cable **36** is set at a relatively constant value. The tower-mounted DC-to-DC converter **42** may be a simple device that down-converts the voltage of the DC power signal by a fixed amount X. The power supply **28** may be programmed to deliver a DC power signal to the tower-mounted DC-to-DC converter **42** that has a voltage level that is set as follows:

$$\text{Voltage of Delivered Power Signal} = V_{RRH\text{-}Max} - V_{margin} + X \quad (4)$$

where $V_{RRH\text{-}Max}$ is the maximum power signal voltage that the RRH **24'** is specified to handle, V_{margin} is a predetermined margin (e.g., 2 Volts), and X is the magnitude of the voltage conversion applied by the tower-mounted DC-to-DC converter **42**.

One disadvantage of the approaches of FIGS. **6** and **7** is that they require the installation of additional equipment (i.e., the DC-to-DC converter **42**) at the top of the tower **30**. As the cost associated with sending a technician up a tower may be very high, there is generally a preference to reduce or minimize, where possible, the amount of equipment that is installed at the top of a cellular base station tower, and the equipment that is installed at the top of cellular towers tends to be expensive as it typically is designed to have very low failure rates and maintenance requirements in order to

reduce the need for technician trips up the tower to service the equipment. The inclusion of an additional DC-to-DC converter **42** also represents a further increase in capital expenditures, which must be weighed against the anticipated savings in operating costs.

Thus, pursuant to embodiments of the present invention, a DC power signal may be supplied to a tower-mounted RRH (or other equipment) of a cellular base station over a power cable, where the DC power signal that is supplied to the RRH may have a relatively constant voltage level, regardless of the current drawn by the RRH. The voltage level of the DC power signal supplied to the RRH may be set to be at or near a maximum power signal voltage that the RRH can handle, thereby reducing the power loss of the DC power signal. In this manner, the operating costs for the cellular base station may be reduced.

In some embodiments, the programmable power supply according to embodiments of the present invention may comprise a DC-to-DC converter that may be connected between a power supply of an existing base station and the power cable that supplies the power signal to a tower-mounted RRH. Thus, by adding a single piece of equipment at the bottom of the tower, an existing cellular base station may be retrofitted to obtain the power savings available using the techniques according to embodiments of the present invention.

While the above-described embodiments of cellular base stations according to embodiments of the present invention include a first, conventional DC power supply **26** and a second DC-to-DC converter power supply **28**, it will be appreciated that in other embodiments these two power supplies may be replaced with a single programmable power supply that may be configured to output a relatively constant voltage at the far end of the power cable **36** in the manner described above.

Pursuant to further embodiments of the present invention, a feedback loop may be used to control the voltage of the DC power signal output by the DC power supply so that the voltage of the DC power signal at the far end of the power cable that connects the power supply and the RRH is maintained at a desired level. FIG. **8** is a simplified, schematic view of one example embodiment of a cellular base station **400** that implements such a technique.

As shown in FIG. **8**, the cellular base station **400** is similar to the cellular base station **100** described above with reference to FIG. **3**, except that the cellular base station **400** further includes a DC power signal voltage control module **50** that is co-located with the RRH **24'**. The DC power signal voltage control module **50** may be located, for example, at or near the top of the tower **30**. In an example embodiment, the DC power signal voltage control module **50** may include a voltage meter **52**, a controller **54** and a communications module **56**. The voltage meter **52** may be used to monitor the voltage of the DC power signal at the far end of the power cable **36** (i.e., at the top of the tower **30**). Any appropriate voltage meter may be used that is capable of measuring the voltage of the DC power signal at the far end off cable **36** (or at another location proximate the RRH **24'**) or that may measure other parameters which may be used to determine the voltage of the DC power signal at the far end off cable **36**.

The voltage meter **52** may supply the measured voltage (or other parameter) to the controller **54**. The controller **54** may then control the communications module **56** to transmit the measured or calculated voltage of the DC power signal at the far end of power cable **36** to, for example, the second power supply **28**. The controller **54** may comprise any appropriate processor, controller, ASIC, logic circuit or the like. The communications module **56** may comprise a wired or wireless transmitter. In some embodiments, the communications module **56** may comprise a wireless Bluetooth transmitter or a cellular transmitter. In other embodiments, the communications module **56** may communicate with the second power supply **28** over a separate wired connection. In still other embodiments, the communications module **56** may communicate with the second power supply **28** by modulating a signal onto the power cable **36**. In each case, the communications module **56** may transmit the measured or calculated voltage of the DC power signal at the far end of power cable **36** to the second power supply **28**. The second power supply **28** may adjust the voltage of the DC power signal that it outputs in response to these communications in order to generally maintain the voltage of the DC power signal at the far end of power cable **36** at a desired and/or pre-selected level. Thus, in this embodiment, an active feedback loop may be used to maintain the voltage of the DC power signal at the far end of power cable **36** at the pre-selected level.

The power signal voltage control module **50** may be a standalone unit or may be integrated with other equipment such as, for example, the RRH **24'**.

While the embodiments that have been described above deliver a DC power signal over the power cable **36**, it will be appreciated that in other embodiments, an AC power signal may be used instead. For example, if the RRHs **24'** are designed to be powered by an AC power signal as opposed to a DC power signal, then the power supply **28** may output an AC power signal as opposed to a DC power signal, but may otherwise operate in the same fashion. Likewise, in embodiments that include a DC-to-DC converter **42** at the top of the tower **30**, an AC-to-DC converter may be used instead or, if the RRH **24'** is designed to be powered by an AC power signal, the DC-to-DC converter **42** may be replaced with a Buck AC-to-AC converter. Thus, it will be appreciated that the embodiments illustrated in the figures are exemplary in nature and are not intended to limit the scope of the present invention.

In the various embodiments described above, a single power cable **36** has been provided that connects the power supply **28** to the RRH **24'**. It will be appreciated, however, that the cabling connection for the power signal between the power supply **28** and the RRH **24'** may include multiple elements such as two or more power cables **36** that are connected by connectors in other embodiments.

A method of powering a radio that is mounted on a tower of a cellular base station according to embodiments of the present invention will now be described with reference to the flow chart of FIG. **9**. As shown in FIG. **9**, operations may begin with a user inputting information to a programmable power supply which may be used by the programmable power supply to set a voltage level of the power signal that is output by the programmable power supply (block **300**). This information may comprise, for example, an electrical resistance of a cabling connection between the power supply and the radio or information regarding the characteristics of the cabling connection that may be used to calculate this resistance. While not shown in FIG. **9**, it will be appreciated that in other embodiments the programmable power supply may have the capability to measure the resistance of the cabling connection, thereby avoiding the need for any user input. The programmable power supply may use this information to output a DC power signal that is provided to the radio over the cabling connection (block **310**). The current of the DC power signal that is output may then be measured

(block **320**). The programmable power supply may then automatically adjust a voltage level of the power signal output by the power supply in response to changes in the measured output current so as to provide a substantially constant, preselected voltage at a first end of the power cable that is remote from the power supply (block **330**). As shown in FIG. **9**, blocks **320** and **330** are then performed continuously at appropriate intervals in order to maintain the voltage level of the signal output of the power supply at the far end of the power cable at the preselected voltage level.

Embodiments of the present invention provide power supplies for powering radio equipment such as a remote radio head that is located remote from the power supply used to power the radio (e.g., the power supply is at the base of a cellular tower and the radio is at the top of the tower) without receiving any feedback from the radio or from other equipment at the remote location. The voltage of the DC power signal supplied by the power supply to the radio over a cabling connection may be set at a pre-selected level. The pre-selected level may be set to reduce or minimize power losses that may be incurred in transmitting the DC power signal over the cabling connection. The voltage of the DC power signal output by the power supply may be varied based on variations in the current drawn from the power supply so that the voltage of the DC power signal at the radio end of the cabling connection may have, for example, a substantially constant value. This value may be selected to be near a maximum value for the voltage of the DC power signal that may be input to the radio.

While typically the voltage of the DC power signal output by the power supply will be adjusted to maintain the voltage of the DC power signal at the radio end of the cabling connection at a set level, it will be appreciated that some variation is to be expected because of the time it takes the DC power supply to adjust the voltage of the DC power signal in response to changes in the current drawn. It will also be appreciated that the voltage of the DC power signal need not be maintained at a constant level at the radio end of the cabling connection but, may instead have different characteristics (e.g., set to be maintained within a predetermined range, set to return to a pre-selected level within a certain time period, etc.) in some embodiments.

In some current cellular systems, the voltage drop that occurs on the DC power signal that is delivered from a power supply located at the bottom of a cellular tower to the RRH at the top of the tower may be so large that the voltage of the DC power signal at the top of the tower may be insufficient to run the RRH. As a result, larger diameter power cables are used in some cases that exhibit less DC resistance and hence a smaller voltage drop. However, the use of larger power cables has a number of disadvantages, as these cables can be significantly more expensive, add more weight to the tower (requiring that the towers be constructed to handle this additional weight) and more difficult to install.

Pursuant to embodiments of the present invention, this problem may be reduced or solved by controlling the voltage of the DC power signal output by the power supply so that the voltage of the DC power signal at the radio end of the cabling connection may be at or near a maximum voltage for the DC power signal that may be input to the RRH. This scheme reduces the voltage drop of the DC power signal, and hence may allow for the use of smaller diameter power cables and/or longer cabling connections between the power supply and the RRH. Additionally, as noted above, as the power losses experienced by the DC power signal are less, the costs of operating the RRH may also be reduced.

The present invention has been described with reference to the accompanying drawings, in which certain embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments that are pictured and described herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout the specification and drawings. It will also be appreciated that the embodiments disclosed above can be combined in any way and/or combination to provide many additional embodiments.

It will be understood that, although the terms first, second, etc. are used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present invention. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

Unless otherwise defined, all technical and scientific terms that are used in this disclosure have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. The terminology used in the above description is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used in this disclosure, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that when an element (e.g., a device, circuit, etc.) is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

It will be further understood that the terms "comprises" "comprising," "includes" and/or "including" when used herein, specify the presence of stated features, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, operations, elements, components, and/or groups thereof.

In the drawings and specification, there have been disclosed typical embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.

That which is claimed is:

1. A method of powering a tower-mounted cellular radio that is remote from an associated baseband unit, the method comprising:

outputting a direct current ("DC") power signal from a power supply and supplying the DC power signal that is output from the power supply to the radio over a power cable;

receiving user input as to a resistance or impedance of the power cable or information from which a resistance or impedance of the power cable can be determined;

adjusting a voltage level of the DC power signal that is output from the power supply, based at least in part on the received user input, so that the DC power signal at a radio end of the power cable that is remote from the power supply has a substantially constant voltage not-

withstanding variation in a current level of the DC power signal that is output from the power supply,

wherein the substantially constant voltage of the DC power signal at the radio end of the power cable exceeds a nominal power signal voltage of the radio so as to reduce power loss in the power cable as compared to the power loss that occurs in the power cable when the DC power signal at the radio end of the power cable is at the nominal power signal voltage.

2. The method of claim **1**, wherein the power supply comprises a programmable power supply.

3. The method of claim **2**, the method further comprising measuring the current level of the DC power signal that is output from the power supply, wherein the voltage level of the DC power signal that is output by the power supply is automatically adjusted in response to changes in the measured current level of the DC power signal that is output from the power supply to provide the DC power signal at the radio end of the power cable that has the substantially constant voltage.

4. The method of claim **2**, wherein the programmable power supply comprises a DC-to-DC converter that receives a DC power signal from a second power supply and adjusts a voltage level of the DC power signal that is received from the second power supply to provide the DC power signal at the radio end of the power cable that has the substantially constant voltage.

5. The method of claim **1**, further comprising transmitting a control signal over the power cable that is used to determine an electrical resistance of the power cable.

6. The method of claim **1**, wherein the substantially constant voltage is higher than a maximum power signal voltage of the radio, the method further comprising using a tower-mounted DC-to-DC converter to reduce a voltage of the power signal at the radio end of the power cable to a voltage that is less than the maximum power supply voltage of the radio.

7. The method of claim **1**, wherein the substantially constant voltage is within 4 Volts of the maximum power signal voltage of the radio.

8. The method of claim **1**, wherein the substantially constant voltage is at least 4 Volts above the nominal power signal voltage of the radio.

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